COMMENT

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Like many recent studies of instrumental climatological records (e.g., Karl, 1985; Jones et *al.*, 1986; Ghil and Vautard, 1991; Karl et *al.*, 1991), Mark Handcock and James Wallis' work aims at identifying possible variations of the Earth's climate over the last century. Their use of a rigorous Gaussion random field (GRF) approach chosen to model surface-air temperatures over part of the northwestern United States is new. The stochastic structure of time series of winter average temperatures at 88 sites belonging to the United States Historical Climatology Network (HCN: Karl et al., 1990) is characterized by this approach, and a temporally stable spatial structure -- with little evidence of temporal dependence -- is found. As a corollary, t-hey derive posterior distributions of the areal-mean temperature over Lime. 'l'his application of their random model indicates that, given a scenario of a gradual increase of 5°F over 50 years, it would take 30-40 more winters of data over this region, for the change to become discernible from natural temperature variations.

length-scale of interannual and interdecadal climatology, which is of the order of several thousand kilometers. Analysis of larger spatial scales could allow inferences as to what part of the long-term signal is regional, and what part characterizes larger areas (Peixoto and Oort, 1984) . Moreover, most temperature changes over the last century have been confined to a relatively short time interval between 1910 and 1940 (Ghil and Vautard, 1991) which predates the time interval studied by Handcock and Wall is.

Over the past half century, the characterization of the Earth climate has shifted from climatology to climate dynamics, from a description of the climatological mean -- with random fluctuations about it -- to a treatment of the climate system as a forced nonlinear oscillator responding dynamically to a variety of deterministic and random forces, active over a wide range of time scales (Ghil and Childress, 198-/). When deviations from the time or space mean of some arbitrarily long interval are the focus of a climatological characterization, longer-period phenomena can be perceived as trends even though they may be purely periodic. A more realistic approach could be to shift attention to shorter-period phenomena of which several cycles are present within a given record. 10 a reasonable approximation, the theory of nonlinear dynamical systems allows us to linearize the system about its time mean over some long interval, in order to study variability over the shorter time scales, as forcing mechanism.. at very different time scales are uncoupled. Results for the shorter time scales provide insights to eventually model the dynamics on the longer time scales. This approach also supports analyses based on less restrictive assumptions (e.g., spatial and temporal inhomogene.ities can be accomodated) . in the remainder of this discussion, we shall illustrate how recent advances in nonlinear dynamics allow us to do just that. A convenient way to reconstruct the dynamics of the climate system from a limited number of uncorrelated time series is by means of empirical orthogonal functions (EOFs) of spatial and temporal variability (Preisendorfer, 1988). A detailed description of this alternative approach to the HCN data is given in Dettinger and Ghil (1992) and in a comparison paper by the discussants (in preparation) .

Providing a complete and accurate description of climate evolution is tantamount to specifying the trajectory of the solution to a system of randomly forced partial differential equations in an infinite?-dimensional phase space. Fortunately, the complexity of such a system is reduced considerably when one considers its projection onto the low-dimensional subspace spanned by the statistically significant part of its dynamics. Within this subspace, the trajectory of the forced dissipative model that captures the essential, deterministic dynamics of the climate system is further confined to an attractor of zero volume. Whitney's (1936) embedding lemma states that if M is the smallest integer larger than the dimension of this attractor, 2M+1 independent variables are sufficient to unequivocally describe the evolution of the dynamical sytem on this attractor. In fact, if one single system variable could be sampled with infinite precision over an infinitely long time interval, Takens theorem (Mañe, 1981; Takens, 1981; Sauer et al., 1991) could be applied to reconstruct dynamics on the attractor by using the univariate time series of that variable and its first 2M time derivatives or, alternatively, 2M+1 Lime-delay coordinates. A refinement of Karhunen-Loève expansion (e.g., Pike et al., 1984) referred to as singular spectrum analysis (SSA: Broomhead and King, 1986; Vautard and Ghil, 1989; Ghil and Vautard, 1991; Vautard et al., 1993) in the climatological literature attempts to do just that. The method has been applied to over a dozen geophysical time series to isolate oscillations from trends, other types of significant variability, and noise (Vautard et al., 1992 - and references therein).

Where observational errors and short records limit our ability to reconstruct a dynamical system's trajectory from the sampled history of one of its variables, a reconstruction of phase space based on time-delayed versions of several system variables can improve the chances of success, provided that the variables are statistically independent. Related to extended ISOF analysis (e.g., Weare and Nasstrom, 1982), multivariate SSA (M-SSA) extends univariate SSA to mixed spatial and temporal directions (Kimoto et al., 1991; Keppenne and Ghil, 1993) to study trajectories of dynamical systems represented by time series of several. system variables. Practically, however, the procedure can become intractable if too many variables are inL~-educed. A judicious way to maximize its effectiveness is to apply it to a small number of leading spatial principal components (S-PCs) resulting from the spatial EOF (S-EOF) analysis of a climatological field (Ghil and Mo, 1991a,b) . This selection guarantees the orthogonality of the selected time series (the S-PCs considered), at least at zero lag, and that. the discarded fraction of the system's variance will be minimized for the number of time series considered (e.g. , Keppenne and Ghil , 1993) .

After an elaborate pre-processing based on the assumption that the spatial correlations have an isotropic homogeneous Gaussian structure but excluding any form of explicit detrending, Dettinger and Ghil (1992) applied S-EOF analysis to the surface-air temperature record from 1910 to 1987 for the conterminous United States. 'l'he analysis delineated the five leading modes (S-EOFs) of spatial variability and their associated S-PCs. Together, these account for 85% of the temperature field's variance. The first S-EOF (S-EOF 1: 39% of associated variance) is representative of temperature variations that are simultaneous and in phase over the whole domain, but varying in amplitude. S-EOF 2 (2"/% of variance) represents temperature variations associated with the east-west temperature gradient. S-EOF 3 (10% of variance) captures the north-south temperature differences. S-EOF 4 (5% of variance) represents center-to-coastal differences, and S-EOF 5 (4% of variance) captures the differences between temperature variations that occur along the northwest-southeast and northeast-southwest directions.

We applied M-55A to adaptively filtered versions of the five leading S-PCs from which all annual and subannual variability had been discarded. The analysis uses the leading M-SSA modes to highlight the structured variability on interannual time scales. The application of maximum entropy spectral estimation (Yule, 1927; Walker, 1931; Burg, 1968; Penland *et al.*, 1991) to the ten leading temporal PCs (T-PCS) helped single out two groups of coupled interannual oscillations (Fig. 1). The first, carried by T-PCs 2-7 (Figs. 1b-1g), consists of three oscillations with periods in narrow frequency bands near 1/10 year-l, 1/3.3 year-l and]/2.3 year-l. The second group consists of a 1.7-year oscillation weakly coupled with a lower-frequency 5.6-year signal; these are carried by T-PCS 8-10 (Figs. 1h-1j). T-PC 1 captures interdecadal variability (Ghil anf Vautard, 1991) as far as the short record permits. To determine the spatial patterns corresponding to the various interannual oscillations, Dettinger and Ghil's S-PCs were projected onto the temporal EOFS corresponding to the two subgroups. The projections indicate which patterns are associated with each temporal oscillation (not shown here). This characterization allows one to interpret the temporal variability captured by M-SSA in terms of known climatic phenomena, such as the quasi-biennial and low-frequency components (Keppenne anti Ghil, 1992; Rasmussen et *al.,* 1990) of the El Niño/Southern Oscillation (e.g., Philander, 1990) .

The non-parametric, data-adaptive approach to the spatio-temporal modeling of climatological fields summarized above provides an alternative to the GRF approach chosen by Handcock and Wallis. Gaussian fields are plausible candidates for climatological modeling, but the usual lack of spatial and temporal homogeneity in fields of pressure and temperature, and the fact that the associated spatial autocorrelation functions are anisotz-epic, are good arguments in favor of a data-adaptive approach, In the latter, rather than being specified a priori , the model's basis functions are dictated by the data themselves.

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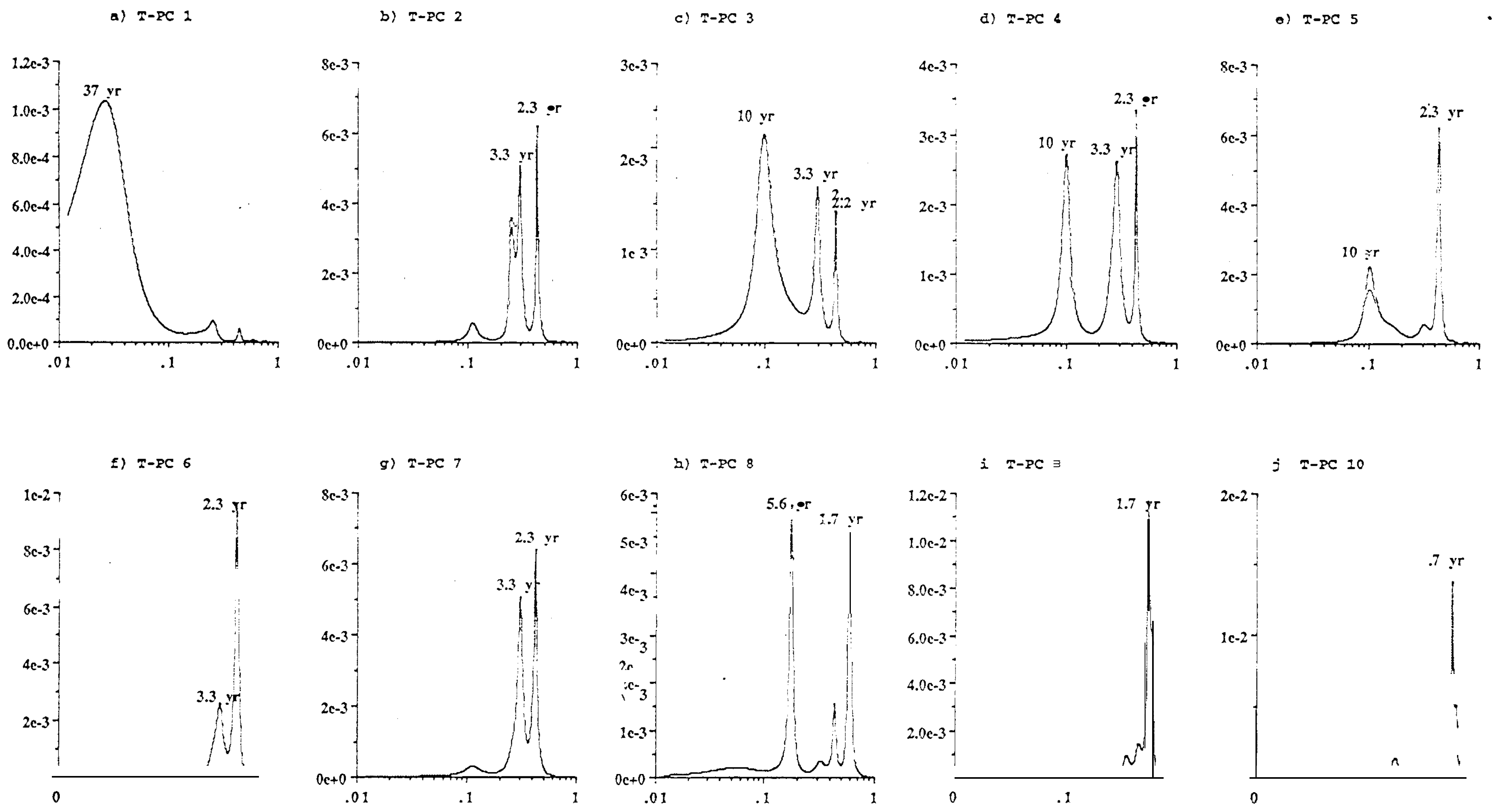
Figure captions

Figure 1. Power spectra of the 10 leading temporal principal components (T-PCs) resulting from the multivariate singular spectrum analysis (M-SSA) of Dettinger and Ghil's (1992) five leading dimensionless spatial PCs (S-PCs). 'l'he logarithmic frequency scales are in cycles/month. 'I'he power spectra of T-PCS 1-10 *were* obtained by the maximum entropy method, after data-adaptive prefiltering (Penland *et al*., *1991)*; they are shown in panels a-j, in that order. Notice the varying linear power-spectral density scales on the ordinates.



Christian L. Keppenne, Michael D. Dettinger and Michael Ghil - Figure 1